

Electric Field effects on quantum correlations in semiconductor quantum dots

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We study the effect of external electric bias on the quantum correlations in the array of optically excited coupled semiconductor quantum dots. The correlations are characterized by the quantum discord and concurrence and are observed using excitonic qubits. We employ the lower bound of concurrence for thermal density matrix at different temperatures. The effect of the Förster interaction on correlations will be studied. Our theoretical model detects nonvanishing quantum discord when the electric field is on while concurrence dies ,ensuring the existence of nonclassical correlations as measured by the quantum discord.

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1 Introduction

In the recent years, the meaning of quantum discords has been attracted a lot of interest because it indicates that entangled states are not the only kind of quantum states exhibiting nonclassical features[1–6]. Quantum discord is a measure of the discrepancy between two natural yet different quantum analogs of the classical mutual information . Quantum discord captures the fundamental feature of the quantumness of nonclassical correlations, which is much like quantum entanglement, but it is beyond quantum entanglement because quantum discord is even present in separable quantum states. Quantum discords have strong potentials in studying dynamical processes[7–10], some quantum information processes such as the broadcasting of quantum states[11, 12] quantum state merging [13, 14], quantum entanglement distillation[15, 16] , entanglement of formation [17]. Besides, there has been considerable interest in the quantum information properties of solid state environment particularly, semiconductor quantum dots (QDs) due to their well defined controllable atom-like and molecule-like properties[18–20]. To study the electro-optical properties of QDs (specially coupled ones), one of the most interesting parameter is the exciton-exciton interaction. This kind of interaction in first neighbors dots will allow to implement a scheme for quantum information processing on QDs [21]. It was shown that the biexcitonic shift due to the dipolar interaction allows for subpicosecond quantum gate operations[22]. It was proven that the optically driven QDs, that are carrying excitons are good candidates for implementation of quantum gates and quantum computation[23–25].

In order to study the amount of concurrence and discord in the array of excitons inside QDs, we employ the lower bound of concurrence for thermal density matrix of identical and equidistant coupled QDs at different bath

temperatures. Furthermore, By the means of electric field, the manipulation of entanglement and discord will be discussed. We show that, quantum correlations may be enhanced upon increasing the temperature and decreased with incresing the electric field across the system. Our theoretical model detects nonvanishing quantum discord, ensuring the existence of nonclassical correlations as measured by the quantum discord

I. 2 THEORY: QUANTUM DOT MODEL AND HAMILTONIAN

The model sample to study the quantum correlation properties of optically driven QDs is a series of InAs coupled QDs with small equal spacing between them along the axis. This model can be realized experimentally(see for example reference[26]). In this model, Förster mechanism[27] is a valid model to explain the energy transfer between QDs through dipolar interaction between the excitons. Here, the qubits are the excitonic electric dipole moments located in each QD which can only orient along ($|0\rangle$) or against ($|1\rangle$) the external electric fields. For such a system, tuning and controlling the quantum correlation between the dipoles is of great importance. The governing Hamiltonian of dipoles in the presence of external electric field simply reads:

$$H = \hbar \sum_{i=1}^n \omega_i [S_z^i + \frac{1}{2}] + \hbar \sum_{i=1}^n \Omega_i \hat{S}_i^z + \hbar \sum_{i=1}^n J_z [S_+^i][S_-^j] + \frac{1}{2} \sum_{i,j=1}^n \lambda [S_+^i S_-^j + S_-^j S_+^i], \quad (1)$$

Where $S_+^i = (|0\rangle\langle 1|)$, $S_-^i = (|1\rangle\langle 0|)$, and $S_z^i = \frac{1}{2}(|0\rangle\langle 0| - |1\rangle\langle 1|)$. ω_i presents the frequency of the excitons in QDs, Ω_i is the frequency related to dipole moment(exciton)

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that is a function of dipole moment and the external electric field (E) at i th QD:

$$\hbar\Omega_i = |\vec{d} \cdot \vec{E}|, \quad (2)$$

Where \vec{d} is the electric dipole moment carried by the exciton that is assumed to be same for each QD. λ presents the Förster interaction which transfers an exciton from one QD to other ones. J_z presents the exciton-exciton dipolar interaction energy, reads:

$$\hbar J_z = \frac{\vec{d}^2(1 - 3\cos^2\theta)}{r_{ij}^3}, \quad (3)$$

where r_{ij} is the distance between dipoles i and j that is assumed along the z axis.

For a qualitative discussion on quantum correlations we assume that the dipole carried by exciton is the one order of magnitude in debyes, a typical experimental electric field 10^6 V/m, so the dipolar interaction parameter ($\hbar J_z$) will be of the order of meV . Förster interaction energy ($\hbar\lambda$) and $\hbar\Omega$ are assumed to be in the order of meV . This values are consistent with experimental observations and calculations[28].

A. 2.1 Lower bound concurrence

Since entanglement is conceived as a resource to perform various tasks of quantum information processing [29–32], knowledge about the amount of entanglement in a quantum state is so important. Indeed, awareness from the value of entanglement, means knowing how well a certain task can be accomplished. The quantification problem of entanglement only for bipartite systems in pure states [33] and two-qubit system in mixed state [34] is essentially solved. In multi-partite systems, even the pure state case, this problem is not exactly solved and just lower bounds for the entanglement have been proposed [35–38]. Here, in order to determination the exact minimum of entanglement between three dipoles(excitons), we use the lower bound of concurrence for three-qubit state which is recently suggested by Li et al. [39]

$$\tau_3(\rho) = \frac{1}{\sqrt{3}} \left(\sum_{j=1}^6 (C_j^{12|3})^2 + (C_j^{13|2})^2 + (C_j^{23|1})^2 \right)^{\frac{1}{2}}, \quad (4)$$

where $C_j^{12|3}$ is terms of the bipartite concurrences for qubits 12 and 3 which is given by

$$C_j^{12|3} = \max\{0, \lambda_j^{12|3}(1) - \lambda_j^{12|3}(2) - \lambda_j^{12|3}(3) - \lambda_j^{12|3}\}. \quad (5)$$

In this notation, $\lambda_j^{12|3}(\kappa)$, ($\kappa = 1..4$), are the square nonzero roots, in decreasing order, of the non-Hermitian matrix $\rho\tilde{\rho}_j^{12|3}$. The matrix $\tilde{\rho}_j^{12|3}$ are obtained from rotated the complex conjugate of density operator, ρ^* , by

the operator $S_j^{12|3}$ as $\tilde{\rho}_j^{12|3} = S_j^{12|3} \rho^* S_j^{12|3}$. The rotation operators $S_j^{12|3}$ are given by tensor product of the six generators of the group $SO(4)$, (L_j^{12}), and the single generator of the group $SO(2)$, (L_0^3) that is $S_j^{12|3} = L_j^{12} \otimes L_0^3$. Since the matrix $S_j^{12|3}$ has four rows and columns which are identically zero, so the rank of non-Hermitian matrix $\rho\tilde{\rho}_j^{12|3}$ can not be larger than 4, i.e., $\lambda_j^{12|3}(\kappa) = 0$ for $\kappa \geq 5$. The bipartite concurrences $C^{13|2}$ and $C^{23|1}$ are defined in a similar way to $C^{12|3}$.

In order to calculate thermal entanglement, we need the temperature dependent density matrix and the density matrix for a system in equilibrium at a temperature T reads: $\rho = \exp(-\beta\hat{H}/Z)$ with $\beta = 1/KT$ and Z is partition function, $Z = Tr(\exp(-\beta\hat{H}))$. In this case, the partition function is

$$Z(T) = \sum_{i=1} g_i e^{-\beta\lambda_i}, \quad (6)$$

where λ_i is the i th eigenvalue and g_i is the degeneracy. and the corresponding density matrix can be written

$$\rho(T) = \frac{1}{Z} \sum_i^N e^{-\beta\lambda_i} |\Phi_i\rangle\langle\Phi_i|, \quad (7)$$

here $|\Phi_i\rangle$ is the i th eigenfunction. The density matrix for our considered system has the form as:

$$\rho(T) = \begin{pmatrix} \rho_{11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho_{22} & \rho_{23} & 0 & \rho_{23} & 0 & 0 & 0 \\ 0 & \rho_{23} & \rho_{22} & 0 & \rho_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_{44} & 0 & \rho_{46} & \rho_{46} & 0 \\ 0 & \rho_{23} & \rho_{23} & 0 & \rho_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_{46} & 0 & \rho_{44} & \rho_{46} & 0 \\ 0 & 0 & 0 & \rho_{46} & 0 & \rho_{46} & \rho_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_{88} \end{pmatrix}, \quad (8)$$

with

$$\begin{aligned} \rho_{11} &= \frac{e^{\beta\lambda}}{1 + e^{\beta(2d+Fz+w)}} \\ &\times [e^{\beta(2d+2Fz+w)} + e^{\beta\lambda} - e^{\beta(2d+Fz+w+\lambda)} \\ &+ e^{\beta(4d+2Fz+2w+\lambda)} + 2e^{\beta(2d+2Fz+w+\frac{3}{2}\lambda)}]^{-1}, \end{aligned}$$

$$\begin{aligned} \rho_{22} &= \frac{1}{3}(1 + 2e^{\frac{3}{2}\beta\lambda}) \\ &\times [(1 + e^{\beta(2d+Fz+w)})(1 + 2e^{\frac{3}{2}\beta\lambda}) \\ &+ e^{\beta(\lambda-2d-2Fz-w)} + e^{\beta(4d+Fz+2w+\lambda)}]^{-1}, \end{aligned}$$

$$\begin{aligned} \rho_{23} &= \frac{e^{\beta(2d+2Fz+w)}(1 - e^{\frac{3}{2}\beta\lambda})}{3(1 + e^{\beta(2d+Fz+w)})} \\ &\times [e^{\beta(2d+2Fz+w)} + e^{\beta\lambda} - e^{\beta(2d+Fz+w+\lambda)}] \end{aligned}$$

$$\begin{aligned}
& + e^{\beta(4d+2Fz+2w+\lambda)} + 2e^{\beta(2d+2Fz+w+\frac{3}{2}\lambda)}]^{-1}, \\
\rho_{44} &= \frac{1}{3}(1 + 2e^{\frac{3}{2}\beta\lambda}) \\
& \times [(1 + e^{-\beta(2d+Fz+w)})(1 + 2e^{\frac{3}{2}\beta\lambda}) \\
& + e^{\beta(\lambda-4d-3Fz-2w)} + e^{\beta(2d+w+\lambda)}]^{-1}, \\
\rho_{46} &= \frac{e^{\beta(4d+3Fz+2w)}(1 - e^{\frac{3}{2}\beta\lambda})}{3(1 + e^{\beta(2d+Fz+w)})} \\
& \times [e^{\beta(2d+2Fz+w)} + e^{\beta\lambda} - e^{\beta(2d+Fz+w+\lambda)} \\
& + e^{\beta(4d+2Fz+2w+\lambda)} + 2e^{\beta(2d+2Fz+w+\frac{3}{2}\lambda)}]^{-1}, \\
\rho_{88} &= e^{3\beta d} \\
& \times [e^{3\beta d} + e^{-3\beta(d+Fz+w)} + 2e^{\beta(d-w+\frac{1}{2}\lambda)} \\
& + e^{\beta(d-w-\lambda)} + e^{-\beta(d+Fz+2w+\lambda)} \\
& + 2e^{-\beta(d+Fz+2w+\frac{1}{2}\lambda)}]^{-1}. \tag{9}
\end{aligned}$$

Since the explicit expressions of solutions of Eq. (7) are very complicated, here we skip the details and give our results in terms of figures. The discussion of results will be postponed to the next section.

B. 2.2 Quantum discord

For a bipartite system AB quantum discord is defined by the discrepancy between quantum versions of two classically equivalent expressions for mutual information [40]

$$D(\rho^{AB}) = I(\rho^{AB}) - C(\rho^{AB}), \tag{10}$$

where $I(\rho^{AB}) = S(\rho^A) + S(\rho^B) - S(\rho^{AB})$ and the classical correlation is the maximum information about one subsystem ρ^A or ρ^B which depends on the type of measurement performed on the other subsystem such as $C(\rho^{AB}) = \max[S(\rho^A) - S(\rho^{AB}|\{\Pi_k\})]$ with $S(\rho) = -\text{Tr}[\rho \log_2 \rho]$ as the von-Neumann entropy. Notice that the maximum is taken over the set of projective measurements $\{\Pi_k\}$ [41].

By definition the conditional density operator $\rho_k^{AB} = \frac{1}{p_k}\{(I^A \otimes \Pi_k^B)\rho^{AB}(I^A \otimes \Pi_k^B)\}$ with $p_k = \text{Tr}[(I^A \otimes \Pi_k^B)\rho^{AB}]$ as the probability of obtaining the outcome k , we can define the conditional entropy of A as $S(\rho^{AB}|\{\Pi_k\}) = \sum_k p_k S(\rho_k^A)$ with $\rho_k^A = \text{Tr}_B[\rho_k^{AB}]$ and $S(\rho_k^A) = S(\rho_k^{AB})$. It has been shown that $D(\rho^{AB}) \geq 0$ with the equal sign only for classical correlation [42].

Very recently, Rulli et al. [43] have proposed a global measure of quantum discord based on a systematic extension of the bipartite quantum discord. Global quantum discord (GQD) which satisfy the basic requirements of a correlation function, for an arbitrary multipartite state $\rho^{A_1 \dots A_N}$ under a set of local measurement $\{\Pi_{j_1}^{A_1} \otimes \dots \otimes \Pi_{j_N}^{A_N}\}$ is defined as

$$\begin{aligned}
D(\rho^{A_1 \dots A_N}) &= \min_{\{\Pi_k\}} [S(\rho^{A_1 \dots A_N} \| \Phi(\rho^{A_1 \dots A_N})) \\
& - \sum_{j=1}^N S(\rho^{A_j} \| \Phi_j(\rho^{A_j}))]. \tag{11}
\end{aligned}$$

Where $\Phi_j(\rho^{A_j}) = \sum_i \Pi_i^{A_j} \rho^{A_j} \Pi_i^{A_j}$ and $\Phi(\rho^{A_1 \dots A_N}) = \sum_k \Pi_k \rho^{A_1 \dots A_N} \Pi_k$ with $\Pi_k = \Pi_{j_1}^{A_1} \otimes \dots \otimes \Pi_{j_N}^{A_N}$ and k denoting the index string $(j_1 \dots j_N)$. We could eliminate dependence on measurement by minimization the set of projectors $\{\Pi_{j_1}^{A_1}, \dots, \Pi_{j_N}^{A_N}\}$. By a set of von-Neumann measurements as

$$\begin{aligned}
\Pi_1^{A_j} &= \begin{pmatrix} \cos^2(\frac{\theta_j}{2}) & e^{i\varphi_j} \cos(\frac{\theta_j}{2}) \sin(\frac{\theta_j}{2}) \\ e^{-i\varphi_j} \cos(\frac{\theta_j}{2}) \sin(\frac{\theta_j}{2}) & \sin^2(\frac{\theta_j}{2}) \end{pmatrix}, \\
\Pi_2^{A_j} &= \begin{pmatrix} \sin^2(\frac{\theta_j}{2}) & -e^{-i\varphi_j} \cos(\frac{\theta_j}{2}) \sin(\frac{\theta_j}{2}) \\ -e^{i\varphi_j} \cos(\frac{\theta_j}{2}) \sin(\frac{\theta_j}{2}) & \cos^2(\frac{\theta_j}{2}) \end{pmatrix},
\end{aligned}$$

with $\theta_j \in [0, \pi)$ and $\varphi_j \in [0, 2\pi)$ for $j = 1, 2, 3$, the equation 10 reduces to

$$\begin{aligned}
D(\rho(T)) &= \min_{\{\theta_j, \varphi_j\}} [S(\rho(T)) \| \Phi(\rho(T))] \\
& - \sum_{j=1}^3 S(\rho^{A_j} \| \Phi_j(\rho^{A_j})). \tag{12}
\end{aligned}$$

By tracing out two qubits, the one qubit density matrices representing the individual subsystems are

$$\rho^{A_{j=1,2,3}} = \begin{pmatrix} \rho_{11} + 2\rho_{22} + \rho_{44} & 0 \\ 0 & \rho_{22} + 2\rho_{44} + \rho_{88} \end{pmatrix}.$$

To find the measurement bases that minimize quantum discord, after some algebraic calculation we have perceived that by adopting local measurements in the σ_z eigen basis for each particle, the value of quantum discord will be minimized. It leads to $S(\rho^{A_j} \| \Phi_j(\rho^{A_j})) = 0$ and

$$\begin{aligned}
S(\Phi(\rho(T))) &= -\{\rho_{11} \log_2(\rho_{11}) + \rho_{88} \log_2(\rho_{88}) \\
& + 3\rho_{22} \log_2(\rho_{22}) + 3\rho_{44} \log_2(\rho_{44})\}. \tag{13}
\end{aligned}$$

The Entropy $S(\rho(T))$ can be obtained as

$$\begin{aligned}
S(\rho(T)) &= -\{\rho_{11} \log_2(\rho_{11}) + \rho_{88} \log_2(\rho_{88}) \\
& + 2(\rho_{22} - \rho_{23}) \log_2(\rho_{22} - \rho_{23}) \\
& + (\rho_{22} + 2\rho_{23}) \log_2(\rho_{22} + 2\rho_{23}) \\
& + 2(\rho_{44} - \rho_{46}) \log_2(\rho_{44} - \rho_{46}) \\
& + (\rho_{44} + 2\rho_{46}) \log_2(\rho_{44} + 2\rho_{46})\}. \tag{14}
\end{aligned}$$

In this case, the time evolution of quantum discord is explicitly obtained as

$$D(\rho(T)) = -3\rho_{22} \log_2(\rho_{22}) - 3\rho_{44} \log_2(\rho_{44}) + 2(\rho_{22} - \rho_{23}) \log_2(\rho_{22} - \rho_{23}) + (\rho_{22} + 2\rho_{23}) \log_2(\rho_{22} + 2\rho_{23}) + 2(\rho_{44} - \rho_{46}) \log_2(\rho_{44} - \rho_{46}) + (\rho_{44} + 2\rho_{46}) \log_2(\rho_{44} + 2\rho_{46})\}. \quad (15)$$

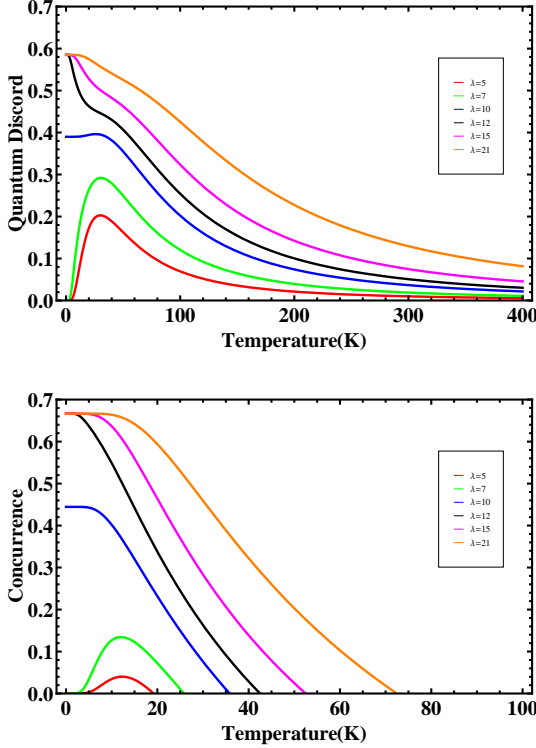


FIG. 1: (Color online) Discord(top panel) and concurrence(bottom panel) measures versus temperature for different values of Förster interaction. Electric field is zero.

II. 3 RESULTS AND DISCUSSION

In what follows, we theoretically test for the existence of quantum discord in aforementioned system containing excitonic qubits and that how it behaves with external electric field. From figures 1, comparing the concurrence and the discord measures at different temperatures shows

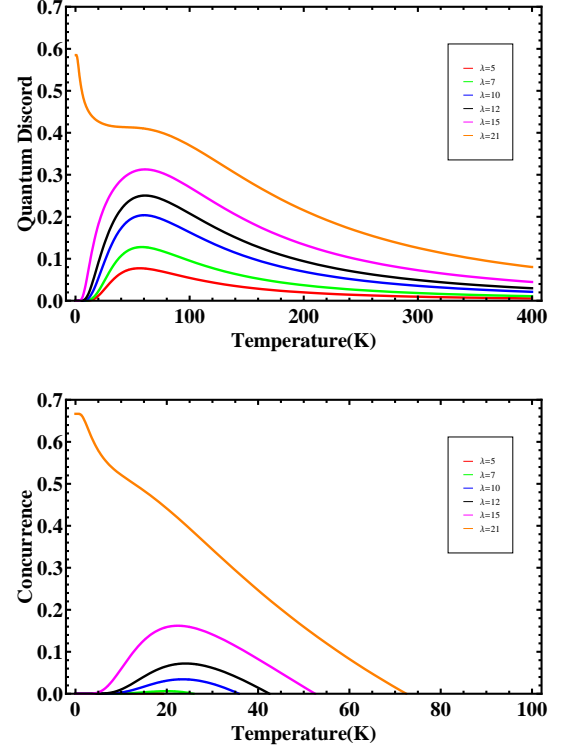


FIG. 2: (Color online) Discord(top panel) and concurrence(bottom panel) measures versus temperature for different values of Förster interaction. The amount of applied Electric field is about 20×10^6 V/m.

that, quantum discord survives at relatively high temperatures where concurrence is zero, also figures depict at very low temperatures both measures yield the same result. At higher temperatures, concurrence suddenly diminishes while quantum discord is still finite, slowly decreasing to zero. This is in accord with the fact that discord quantifies nonclassical correlations beyond entanglement. Generally, both quantum correlations decay with temperature due to thermal relaxation effects. Figures demonstrate that when electrical bias is off the quantum correlations increase monotonically with increasing Förster interaction. This can be explained in terms of the increasing excitonic interaction that leads to increase the correlations. At Förster interactions higher than about 10meV and at temperatures smaller than 20K , concurrence is slightly larger than discord. In contrast, at lower Förster interactions the opposite trend is observed and

discord overcomes the concurrence almost for all temperatures that is because of as mentioned fact that discord indicates nonclassical correlations beyond entanglement even when λ is low. From figures it is clear that at lower λ , Temperature helps to make the correlations so that for very low temperatures, till about $20K$ (for discord) and $10K$ (for concurrence), discord and concurrence increase with increasing temperature due to the thermal entanglement effects[44].

Figures 2 displays discord and correlation measures when $\hbar\Omega$ is assumed to be 2.5 meV that corresponds to the electric field(E) of about $20 \times 10^6 \text{ V/m}$ (this small value for electric field can be realized by experiments very easily). It is clear that discord and concurrence are smaller than that of observed in figure1. This indicates that turning electric field on, decreases the correlations. It is because electric field makes all the dipoles align in the same direction that results in increasing dipolar repulsive interaction that immediately leads to the reduction of coulomb induced correlations[45]. For all the values of λ the discord is survived with increasing E while the concurrence dies for smaller λ . Our results shows that increasing the electric field overcomes the effect of Förster interaction and removes the concurrence for all values of λ , however, nonzero discord can still be observed for higher values of electric field(figure3). This manifests the importance of discord to measure the quantum correlations.

III. 4. CONCLUSIONS

In summary, We studied the quantum discord and concurrence measures in the array of optically driven coupled

quantum dots. Qubits are excitons in each quantum dot that can be model by dipoles. We used the lower bound of concurrence for thermal density matrix of identical and equidistant coupled QDs at different temperatures. We found that the discord and concurrence are enhanced by increasing the parameter of Förster interaction that is resulted by increasing correlations with increasing this parameter. For very low temperatures and higher Förster interaction, concurrence is slightly larger than discord. In stark contrast, at low Förster interactions the opposite trend is observed. Also in very low temperature region, because of thermal entanglement, both measures increase and then tend to zero for higher temperatures induced by thermal relaxation effects. We observed that switching electric field on, correlations diminish, however, discord is survived while concurrence dies for the all values of Förster interaction. It is because electric field makes all the dipoles to be parallel that results in increasing dipolar repulsive interaction and finally decrease the entanglement.

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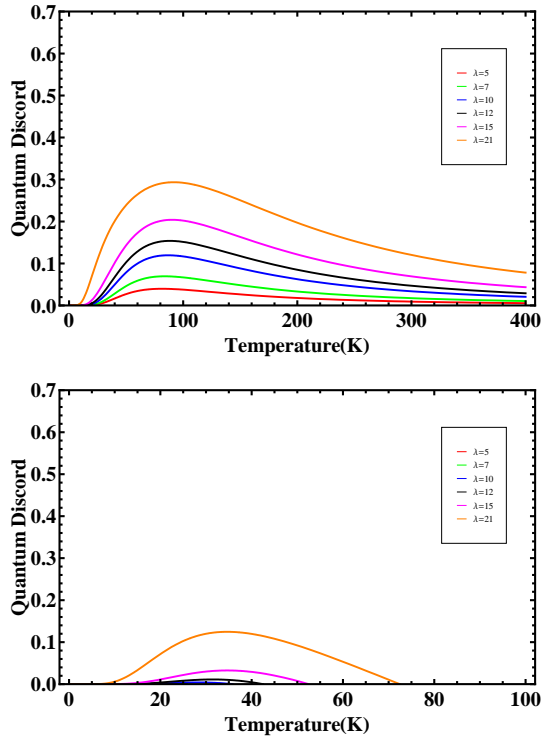


FIG. 3: (Color online) Discord(top panel) and concurrence(bottom panel) measures versus temperature for different values of Förster interaction. The amount of applied Electric field is about 40×10^6 V/m.

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